



Net energy analysis of a solar combi system with Seasonal Thermal Energy Store

Colclough, S., & McGrath, T. (2015). Net energy analysis of a solar combi system with Seasonal Thermal Energy Store. *Applied Energy*, 147, 611-616. DOI: 10.1016/j.apenergy.2015.02.088

Published in:
Applied Energy

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights
© Elsevier 2015.

This manuscript version is made available under the CC-BY-NC-ND 4.0 license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits distribution and reproduction for non-commercial purposes, provided the author and source are cited.

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Manuscript Number:

Title: Net Energy analysis of a Solar Combi System with Seasonal Thermal Energy Store

Article Type: Original Paper

Keywords: Seasonal Thermal Energy Storage; STES; Passive House; Life Cycle Analysis; Net Energy Ratio

Corresponding Author: Dr. Shane Colclough,

Corresponding Author's Institution: University of Ulster

First Author: Shane Colclough

Order of Authors: Shane Colclough; Teresa McGrath

Abstract: EU targets require nearly zero energy buildings by 2020. However few reviews exist of how this has been achieved in practise in individual residential buildings. This paper presents a carbon analysis of a real installation based on the recorded performance of a low-energy house in combination with a solar DHW and space heating system which incorporates a seasonal thermal energy store. Key findings for the project are presented including the recorded DHW and space heating demand, the performance of the solar system including the Seasonal Thermal Energy Store (STES) and the results of an embedded carbon and operational carbon analysis of the heating system. The life cycle energy consumption and life cycle carbon analysis in addition to net energy ratios, are calculated for five heating system scenarios.

Net Energy analysis of a Solar Combi System with Seasonal Thermal Energy Store

Authors

Shane Colclough*, University of Ulster, Newtownabbey, BT370QB, Northern Ireland, UK.

S.Colclough@ulster.ac.uk, +442890366907

Ms Teresa McGrath, PhD Researcher, School of Planning, Architecture & Civil Engineering, Queens University Belfast, NI, UK.

* Corresponding Author

Abstract

EU targets require nearly zero energy buildings (NZEB) by 2020. However few monitored examples exist of how NZEB has been achieved in practise in individual residential buildings. This paper provides an example of how a low-energy building (built in 2006), has achieved nearly zero energy heating through the addition of a solar domestic hot water and space heating system (“combi system”) with a Seasonal Thermal Energy Store (STES). The paper also presents a cumulative life cycle energy and cumulative life cycle carbon analysis for the installation based on the recorded DHW and space heating demand in addition to energy payback periods and net energy ratios. In addition, the carbon and energy analysis is carried out for four other heating system scenarios including hybrid solar thermal/PV systems in order to obtain the optimal system from a carbon efficiency perspective.

Keywords:

Seasonal Thermal Energy Storage, STES, Passive House, Life Cycle Analysis, Net Energy Ratio

1. Introduction

The European Union "20-20-20" commitment set three key objectives for 2020:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20% improvement in the EU's energy efficiency.

Given that 40% of energy is consumed in buildings, EU Member States have committed to implementing nearly-zero energy buildings by 2020 through the adoption of the recast Energy Performance of Buildings Directive [1]. Article 9 of the Directive states:

“Member States shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings”.

A nearly zero-energy building is defined in Article 2 of the EPBD recast as

“a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby”.

In considering how best to achieve Net Zero Energy Buildings in practice, a number of studies have considered how existing low-energy standards such as the Passivhaus standard [2] could be used as the basis for achieving NZEB for example Musall & Voss [3] and Hermelink et al [4], including when used in conjunction with renewables such as solar energy e.g. Mohamed et al [5].

A number of studies have carried out Life Cycle Assessments (LCA) of low energy houses such as those constructed to the Passivhaus standard [6]. Other studies eg Leckner & Zmeureanu [7] have performed the LCA of Net Zero Energy Houses when used in conjunction with Solar Combisystems. Further studies such as Saman [8] and Ayman et al [9] have looked at different methodologies for achieving NZEB with Ayman et al specifically considering use of the Passive House with Solar Heating. Coa [10] considers the challenges of the implementation of a hybrid renewable energy system to meet the reducingly carbon intensive energy demands. However despite much working being done on the approach to achieving NZEB, given that building regulations in European countries to date have not required NZEB, few monitored examples exist of how existing buildings have achieved NZEB. This paper provides an example of how a low-energy building (built to the Passivhaus standard in 2006), has achieved nearly zero energy heating through the addition of a solar domestic hot water and space heating system (“combi system”) with a Seasonal Thermal Energy Store (STES). The paper also considers a carbon analysis of a number of potential heating systems in order to obtain the optimal system from a carbon efficiency perspective. In order to do so a number of approaches are used including the cumulative energy and cumulative carbon consumption and the Net Energy Ratio.

1.2 The Passive House

The Passive House building standard specifies a space heating demand of less than $15 \text{ kWhm}^{-2}\text{a}^{-1}$ [2] and is a voluntary low-energy standard which has seen widespread adoption, with over 50,000 examples having been built over the past 20 years [11]. The study of buildings constructed to the Passive House building standard allows us to gain an insight into how the nearly zero-energy buildings which are now mandated will perform in the future.

1.3 Application of solar seasonal thermal energy storage

A number of methods have been employed to address the remaining Passivhaus space heating demand and domestic hot water demand through the use of renewable sources on or close to the site. The approach which is used is typically tailored to the specifics of the site in question, often through the application of solar energy.

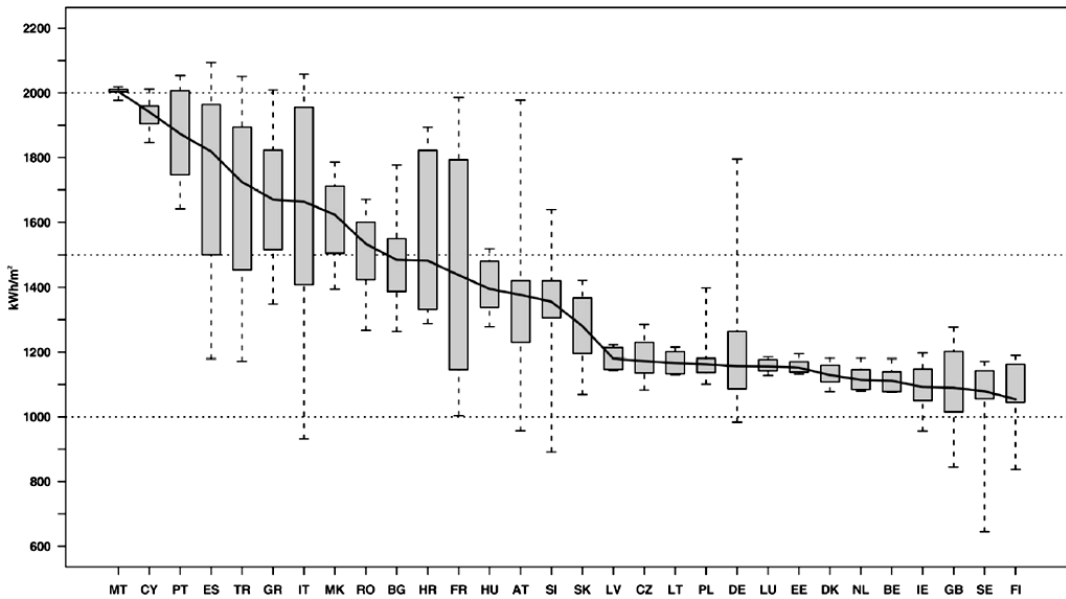


Figure 1. Yearly Global Radiation Incident on Optimally Inclined Plane in European Countries [12]

The usefulness of solar gain for heating buildings is a function of the ratio of incidental insolation to heat loss [13]. Figure 1 above shows that the average global solar radiation (represented by the continuous black line) experienced in Ireland is similar to that experienced in Germany, the country

with the fourth largest penetration of solar thermal systems in Europe [14]. In Temperate Maritime Climates (TMC) the long heating season coupled with the low peak space heating demand in winter means that the solar resource in Temperate Maritime Climates provides a good match with the space heating demand for energy efficient buildings [15].

By sizing solar thermal installations to meet the space and domestic hot water demands in spring and autumn, a significant portion of the annual heating demand can be met with solar. By integrating this system with a Seasonal Thermal Energy Store (STES), a portion of the surplus heat from the summer can be stored for winter use, thereby further increasing the solar fraction.

Dincer, I. & Rosen, [16] recognised the advantages of saving low-cost heat using a Seasonal Thermal Energy Store. Applying the principle of storing low-cost surplus thermal energy from a domestic hot water and space heating installation, it has been demonstrated that it is possible to supply over 70% of the heating needs of a Passive House through the application of STES in a TMC [17].

The most common seasonal thermal energy stores are Aquifer Thermal Energy Stores (ATES) and Borehole Thermal Energy Stores (BTES). However both of these require suitable ground conditions that do not always exist [16], leading to the requirement for a tank based STES solution.

The size of STES is also important to consider, as efficiency and economic viability improve with scale [18]. This suits countries where community-based heating systems are common such as the Netherlands, which currently has the largest number of STES installations in Europe [19]. However, in countries where the largest proportion of houses built are individual dwellings (such as in Ireland with 62.3%, 60.8% and 57.0% for 2011, 2012, 2013 respectively [20]), community-based systems are not appropriate requiring consideration of STES for individual dwellings. Individual dwellings also often afford the advantage of providing sufficient land for the installation of a seasonal thermal energy store.

Thus, this study considers the application of aqueous STES for the single dwelling.

2.0 Case study performance

The dwelling under consideration is a 215m² detached Passive House constructed in 2006. A solar installation comprising 10.6 m² evacuated tube solar array 300l Domestic Hot Water (DHW) tank, 23m³ aqueous Seasonal Thermal Energy Store (STES) and combined underfloor and Heat Recovery and Ventilation (HRV) space heating system was installed and has been monitored since June 2009. The installation has been described previously [17] along with the maximum theoretical solar fraction [21] and a high level carbon analysis of the installation [22].

The DHW demand over the period considered was 705kWh (with solar contribution of 629kWh), reflecting the use of the dwelling as an office. Of the total space heating demand of 1592 kWh between June 2010 and May 2011, only 450 kWh was borne by the electric heating system. The Solar Fraction (SF) over the heating season was 72%, with 739 kWh (46%) of the total space heating demand being met by direct space heating, and the remaining 406 kWh (26%) by means of inter seasonally stored heat [22].

3.0: Life cycle energy & carbon analysis

3.1 The context of the carbon analysis

A review study by Sartori & Hestnes [23] that examined 60 case study buildings, both conventional and low-energy, found that as operational energy was reduced the relative importance of the embodied energy was increased. Conventional buildings had an embodied energy of between 2-38% of total life cycle energy whilst the embodied energy of low energy buildings was between 9-46%. Of particular interest in this review is a zero-energy solar house, as discussed further by Ramesh et al., [24], which has such a high embodied energy from the use of photovoltaic panels that it exceeds the total life cycle energy of some low-energy buildings. As such when operational energy levels are

reduced to very low levels and employ significant amounts of renewable technologies a focus is required on the embodied energy and carbon of the systems employed in order to ensure there is a net benefit in terms of life cycle energy and carbon. This study does not analyse the embodied energy of the dwelling (in this case a Passive House), but rather focuses on the heating system required in order to produce the relatively small heating energy needed. Thus, the paper is examining the carbon efficiency of the renewable heating element exclusively using the life cycle assessment (LCA) framework as standardised in ISO 14040-ISO14044 series.

3.2 Assumptions and approach

A number of assumptions were made in regard to the expected service life, maintenance requirements and performance of installed systems for the purpose of performing the carbon analysis.

Solar thermal is a mature technology, the various components carry long warranties and it is anticipated that with minimal intervention, systems will continue to operate for a service lives of 15 to 40 years [25]. Typical warranties for solar collectors are 10 years with some manufacturers offering 20 year warranties [26], with warranties of up to five years typical for pumps, while tanks have lifetime warranties.

In this analysis, scheduled maintenance of the system is assumed to be every six years, and it is assumed that the solar thermal system will continue to operate for 20 years without further capital investment. Unless otherwise stated, the analysis has assumed that the viability of all equipment (with the exception of the STES) at the end of the 20 year period is zero. However, while this is a reasonable assumption in the case of the DHW and space heating systems, the STES has been assumed to have the same service life as the building i.e. 80 years.

It is assumed that a replacement of the solar collector, DHW and direct space heating and seasonal energy storage heat exchanger coils will be required at year 20. It is assumed that the seasonal energy storage tank and DHW tank will not require any extra maintenance at 20 years.

There are environmental impacts and energy consumed for the extraction, production and assembly of the materials used in the heating system. The ISO 14040 series life cycle assessment framework, can be used to quantify these environmental impacts.

Two of the most common indicators calculated are embodied energy (MJ) and embodied carbon dioxide equivalent (kgCO_{2e}). Embodied energy includes all the energy consumed in the different stages of a products life such as extraction, production and transport. Embodied carbon accounts for the amount of greenhouse gas emissions that have been produced during the different stages of manufacture and use over a product's life.

At the time of writing the Sustainable Energy Authority of Ireland was developing a methodology for the measurement of embodied energy and carbon for applications in life cycle assessment of buildings. This methodology is based around the ISO 14040 and ISO 14044; which detail the life cycle assessment framework and the PAS:2050 for the calculation of greenhouse gas emissions. As this database was still in compilation for the Republic of Ireland, other sources were used to approximate the embodied energy and carbon in this study. See Table 1.

The EcoInvent database was used to approximate the embodied energy and carbon associated with the different possible configurations of equipment that could fulfil the space and water heating requirements of the building.

The life cycle impact assessment method used within Simapro was the International Panel on Climate Change (IPCC) Global Warming Potential 2007 100a method and Cumulative Energy Demand (CED) method which calculated the embodied carbon (kgCO_{2e}) and embodied energy (MJ) respectively. The CED method provides a result that corresponds to the total amount of primary energy used over a products life cycle to deliver 1MJ of heating. Primary energy sources consist of conventional sources such as fossil fuels, nuclear, hydropower and renewable energy sources including solar, geothermal, biomass etc.[27]. Embodied carbon is not limited to carbon dioxide emissions only but includes other greenhouse gases such as methane (CH₄) and nitrous oxides (NO_x).

Material / Process	Quantity	Unit		Cases
Propylene glycol, liquid, at plant /RER	19	kg	EcoInvent	2,3,4,5
Stainless steel hot rolled coil, annealed & pickled, elec. Arc furnace routr	153.03	kg	ELCD	1,2,3,4,5
Tube insulation, elastomere, at plant/DE	1.12	kg	EcoInvent	4,5
Copper sheet, technology mix, consumption mix, at plant, 0.6mm thickness EU-15	20.68	kg	ELCD	4,5
Inverter, 500W, at plant/RER/I	1	number	EcoInvent	4,5
Photovoltaic panel, multi-Si, at plant/RER	5	m ²	EcoInvent	4,5
Polystyrene foam slab, at plant/ RER	584.71	kg	EcoInvent	4,5
Cellulose fibre, inclusive blowing in, at plant?CH	467.136kg	kg	EcoInvent	4,5
Concrete, normal at plant/CH	5.9	m ³	EcoInvent	4,5
Foam glass, at plant/RER	15.57	kg	EcoInvent	1, 2, 3,4,5
Heat, at tube collector, one family-house, for combined system / CH	80	MJ	EcoInvent	2,3,4,5
Pump 40W, at plant/CH/I	1	number	EcoInvent	2,3,4,5
Evacuated tube collector, at plant/GB/I	10.6	m ²	EcoInvent	2,3,4,5
Expansion vessel 25L at plant/CH/I	1	number	EcoInvent	2,3,4,5
Auxiliary heating, electric, 5 kW, at plant/CH/I	1	number	EcoInvent	2,3,4,5
Heat pump RER/I	0.00001	number	EcoInvent	1,2,3 4,5
Electricity, PV, at 3kWp slanted-roof, ribbon-Si, panel, mounted /CH	574	kWh	EcoInvent	5

Table 1. Embodied Energy and Carbon metrics

These gases are multiplied by Global Warming Potential (GWP) factors, as defined by the IPCC, allowing them to be expressed in the terms of carbon dioxide equivalent. The IPCC have developed three time horizons of 20, 100 and 500 years with 100 year horizon most common.

3.3 Operational energy & carbon analysis

During the period under consideration, the total solar space heating contribution was 1142 kWh. During the same period, solar contributed 629kWh of the DHW load, giving a total solar contribution of 1771kWh. Operation of the solar pump consumed 35.1kWh and operation of the underfloor/HRV

HX pump consumed 43.8kWh over the heating period, giving a total of 78.9kWh. Subtracting the consumed 78.9 kWh from the 1771 kWh electricity saved, gives a balance of 1692 kWh. Thus there is a carbon emissions saving of 878 kg of CO₂ pa using the figure of 481g per kWh [28]. Had the total DHW and space heating load of 2298kWh been met by electricity, the emissions would have been 1192kg. Thus a carbon emissions reduction of 75.3% was achieved for the actual installation over the period of monitoring.

In order to understand if the current configuration of the system is the optimal system from a life cycle and operational carbon emissions perspective, five scenarios are considered. They range from considering a wholly electric heating system (Case 1) which represents the smallest investment in both capital cost and embodied energy (but the highest operational energy consumption), through to one which is wholly solar (Case 5), representing the highest cost and embodied energy, but the lowest operational energy consumption. See Table 2.

Case	Energy source	DHW {kWh}	Space Htg {kWh}	Total {kWh}	Total Solar & Electric {kWh}
1	Solar Thermal	0	0	0	2297
	Electric (grid)	705	1592	2297	
2	Solar Thermal	682	0	682	2332
	Electric (grid)	58	1592	1650	
3	Solar Thermal	629	739	1368	2332
	Electric (grid)	111	853	964	
4	Solar Thermal	629	1142	1771	2376
	Electric (grid)	111	494	605	
5	Solar Thermal	629	1142	1771	2376
	Solar Electric	111	494	605	

Table 2. Solar, Electric and Total Energy consumption for DHW and Space Heating

Case 1: Electric domestic hot water and space heating

The base case of electric heating for Domestic Hot Water and space heating is considered in case 1. As can be seen from Table 2, the total domestic water and space heating demand is met using the electricity network, giving a total electrical network consumption of 2297 kWh.

Case 2: Solar domestic hot water in addition to electric DHW and space heating

In this scenario, a typical 3.6 m² of evacuated tube solar collectors is used (via a heat exchanger coil) to heat the domestic hot water. Backup DHW heating is provided by the existing 3 kW immersion heater. Space heating continues to be provided by electricity.

Given the relatively low DHW consumption of 705 kWh, in order to make meaningful comparisons, the PHPP was used to calculate the solar DHW production for an evacuated tube array of 3.6 m² coupled with a 300 L tank, and the average monthly DHW demand was used to estimate the annual solar fraction and therefore the solar heat in kWh.

Case 3: solar DHW and space heating in addition to electric DHW and space heating

In order to provide for space heating in addition to the domestic hot water system, the solar collector is increased to 10.6 m² of evacuated tubes and a water to air heat exchanger is added to the existing heat recovery and ventilation system. Thus, in this scenario, the relatively high embodied energy of the seasonal thermal energy store is avoided, while the benefit of the (relatively small) STES contribution to the space heating demand is forgone.

Case 4: addition of the STES to the solar system

This case represents the figures from the actual installation monitored and provides the base data from which the other scenarios are derived. The facility to store excess summer heat for use during the winter is provided by the addition of an aqueous STES to the existing domestic hot water and space heating solar system. As can be seen from table 2, more operational energy is consumed in this case due to the extra electricity required to operate the pump which transfers the seasonally stored heat from the STES to the house. The transfer of 450 kWh of heat from the seasonal store requires 44 kWh of electricity to operate the pump.

Case 5: addition of a PV solar array

While monitoring has shown that the solar thermal systems considered in case 4 can provide 72% of the space heating needs, the shortfall in the zero carbon heating objective could potentially be met with the addition of a photovoltaic solar array. In this scenario it is assumed that the DHW and Space Heating electrical needs of 605kWh can be met with a PV array of 4.95m². This assumes that electricity net metering is available. Table 2 demonstrates that no grid electricity is used, with solar energy providing all of the electricity required to meet the DHW and space heating needs. The embodied, operational and maintenance energy and carbon of the different possible configurations of domestic hot water and space heating requirements for cases 1-5 are shown in Table.

	Case 1	Case 2	Case 3	Case 4	Case 5
Energy					
Initial embodied energy (MJ)	1153.67	3079.94	6580	27926	32944
Annual operational energy (MJ)	8269	5940	3470	2178	0
Expected maintenance energy (MJ)	0	22117	69331	69331	123758
Carbon					
Initial embodied carbon(kgCO ₂ e)	475	913	1550	5850	6680
Annual Operational carbon(kgCO ₂ e)	1192	856	500	314	0
Expected maintenance carbon	0.00	1231.34	3839.71	3839.71	6239.71

Table 3. Embodied, operational and maintenance energy and carbon for case 1-5

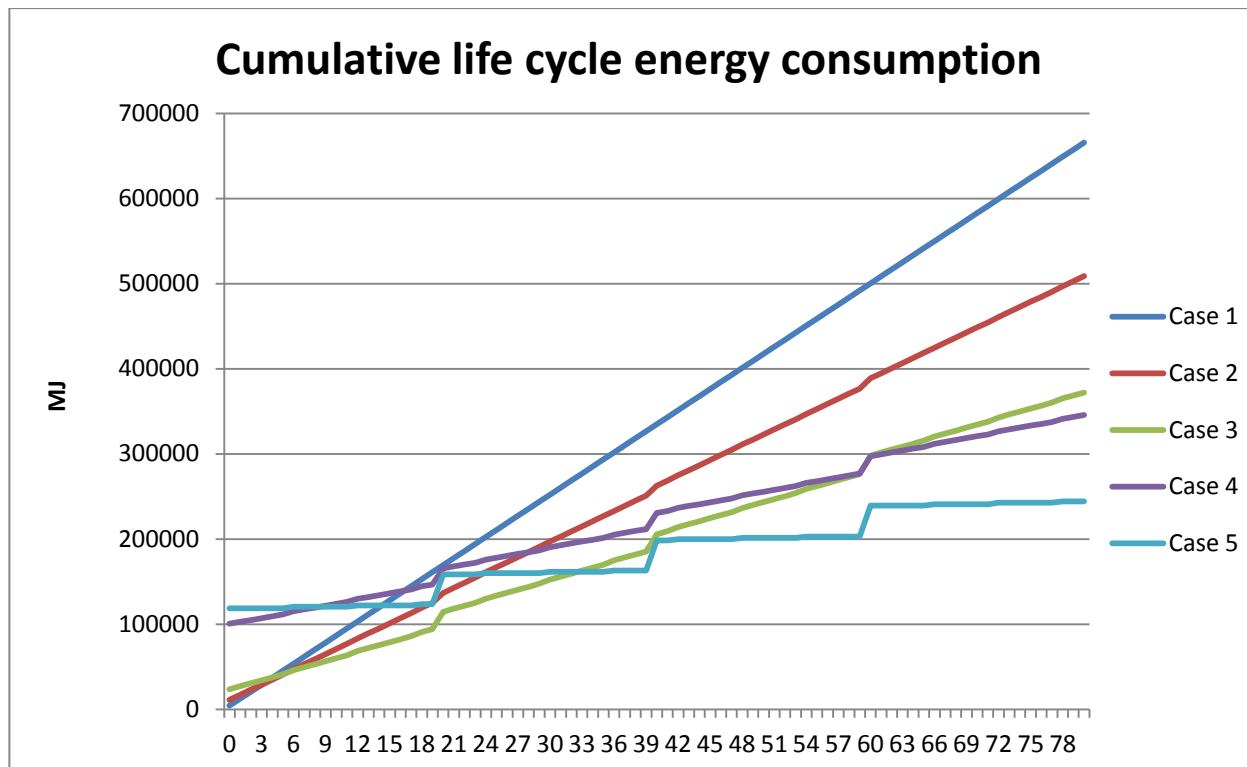


Figure 2. Life cycle energy consumption including embodied, operational & maintenance requirements

Figures 2 and 3 show the cumulative life cycle energy and carbon for each of the five cases. Embodied energy and carbon are represented by the initial year zero. Maintenance requirements such as replacing the solar fluid at six year intervals and replacing evacuated tubes and solar panels at twenty year intervals have been included. Case 1 whilst having the lowest embodied energy and carbon and maintenance, has the highest life cycle impact as operational demand is met by a non-renewable electrical supply source. Case 5 whilst having the largest initial investment in terms of carbon and energy has the lowest associated life cycle impact.

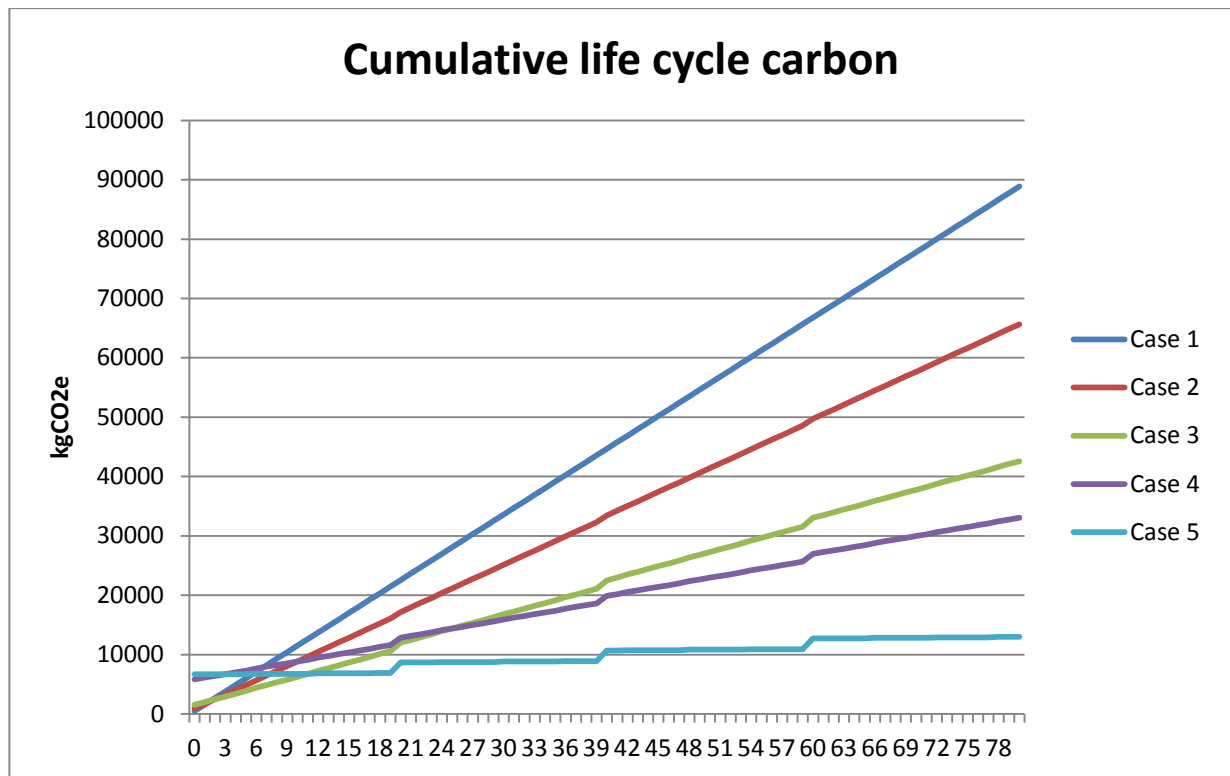


Figure 3 Life cycle carbon production including embodied, operational and maintenance.

To evaluate the performance of each of the five case studies the energy savings, energy payback and the net energy ratio of each of the five cases were calculated. The energy savings are calculated by considering the primary energy factor of the power source and the efficiency of the system.

$$\text{Energy Savings} = \frac{\text{Solar Output} \times \text{Primary Energy Factor}_{\text{Aux heating}}}{\text{Efficiency}_{\text{Aux heating}}} - \frac{\text{Electricity Used by Pump}}{\text{Primary Energy Factor}_{\text{Electricity}}}$$

$$\text{Energy Payback} = \frac{\text{Embodied energy}}{\text{Annual energy savings}}$$

$$\text{NER} = \frac{\text{Annual energy savings} \times \text{service life}}{\text{Embodied energy}} = \frac{\text{Service life}}{\text{Energy payback}}$$

	Case 1	Case 2	Case 3	Case 4	Case 5
Energy savings {MJ}	0	8239.5	16574.5333	21412.45	28763.07
Energy payback {Years}	N/A	4.03	5.61	7.93	8.43
NER	0	5.0	3.6	2.5	2.4

Table 4 Energy Savings, Energy Payback and Net Energy Ratio per Case Considered

4.0 Discussion and Conclusions

Figures 2 and 3 demonstrate that the most attractive option from the perspective of cumulative life cycle carbon emissions and life cycle energy consumption over any time period in excess of 33 years is that represented by case 5 i.e. that which makes the maximum use of both solar thermal and photovoltaic solar energy.

Both figures also clearly demonstrate that the largest investment of both energy and carbon is that represented by case 5 due to the highest embodied energy.

Considering the cumulative life cycle energy, case 2 is a more attractive option than case 1 from year four, with case 3 being more attractive than case 1 or 2 for any period exceeding six years. Due to the high embodied energy of case 4 as it is currently configured, the analysis shows)despite becoming more attractive than case three in year 59), case 5 has already become the most attractive proposition from year 34.

When one considers the analysis from the perspective of cumulative life cycle carbon (figure 5), both case 2 and case 3 become more attractive than case 1 in year two. Case 4 is never the most attractive option, with case 5 becoming the most attractive option for any time periods considered in excess of 12 years.

Table 4 shows that, despite having the lowest energy savings, case 2 represents the most attractive proposition from the energy payback and net energy ratio perspectives given the relatively small energy investment and high energy savings possible due to the high solar fraction for the DHW.

Consideration of case three demonstrates that the energy savings can be doubled for an additional "investment" of 1.57 years in terms of energy payback, with the consequential reduction in the net energy ratio from 5.0 to 3.6. The net energy ratios of case 4 and five are very similar at 2.5 and 2.4 respectively, representing the larger energy investment under consideration.

Overall, the analysis demonstrates that in achieving the energy savings outlined in table 4, care needs to be taken in choosing the correct metrics such that the appropriate objective is achieved. This analysis has shown, that for the Passive House monitored, consideration of the Net Energy Ratio leads to the addition of a modest solar thermal array for domestic hot water heating being the most attractive proposition for reducing the already small energy demand. Considering the objective of achieving lowest cumulative energy, the installation of a combined solar thermal energy system and seasonal thermal energy store with supplementary photovoltaic array is not attractive until year 34. However, such a system is attractive for any periods exceeding 12 years if the objective is to achieve the lowest cumulative life cycle carbon emissions.

Another key finding is that while the solution incorporating the STES in combination with PV is the most attractive proposition from a life cycle carbon emissions perspective, the specific STES installation considered has a high embodied energy, which impacts significantly in the analysis.

Previous analysis has shown that the STES under consideration has significantly reduced the energy consumption and is financially viable [17]. In the planning of such systems in the future, consideration also needs to be given to the optimisation of STES installations from an embodied energy and carbon perspective, ideally at the design stage.

Finally, it should be noted that previous analysis has demonstrated that the significant increase in energy savings (in the order of 50%) could be achieved through relatively modest changes in the solar installation. Even without optimising the STES from the embodied energy perspective, such changes would have a significant impact on the analysis by making case 4 and five significantly more attractive. Further work needs to be done in analysing STES installations from a carbon perspective in order to obtain a more holistic perspective on the attractiveness of STES installations from a life cycle carbon perspective.

5.0 Acknowledgements

This work was undertaken as part of the Irish Governments Charles Parsons Initiative

6.0 References

- [1] EPBD, 2010 DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings (recast) available from <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF>
- [2] IPHA, International Passive House Association. Passive House certification criteria. Available http://www.passivehouse-international.org/index.php?page_id=150&level1_id=78 [Last accessed April 2, 2014]
- [3] MUSALL, E. and VOSS, K., 2012. The Passive House Concept as Suitable Basis towards Net Zero Energy Buildings. , *Tagungsband 16 Internationale Passivhaustagung 2012*, pp. 271–276.
- [4] HERMELINK, A., SCHIMSCHAR, S., BOERMANS, T., PAGLIANO, L., ZANGHERI, P., ARMANI, R., VOSS, K. and MUSALL, E., 2013. *Towards nearly zero-energy buildings Definition of common principles under the EPBD. BESDE10788*. Available from http://www.nezeh.eu/assets/media/fckuploads/file/Reports/2.nzeb_full_report.pdf: Ecofys.
- [5] MOHAMED, A., HASAN, A. and SIRÉN, K., 2014. Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives. *Applied Energy*, **114**(0), pp. 385-399.
- [6] STEPHAN, A., CRAWFORD, R.H. and DE MYTTENAERE, K., 2013. A comprehensive assessment of the life cycle energy demand of passive houses. *Applied Energy*, **112**(0), pp. 23-34.
- [7] LECKNER, M. and ZMEUREANU, R., 2011. Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. *Applied Energy*, **88**(1), pp. 232-241.
- [8] Saman
- [9] AYMAN, M., HASAN, A. and SIRÉN, K., 2014. Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives. *Applied Energy*, **114**(0), pp. 385-399.
- [10] CAO, S., HASAN, A. and SIRÉN, K., 2014. Matching analysis for on-site hybrid renewable energy systems of office buildings with extended indices. *Applied Energy*, **113**(0), pp. 230-247.
- [11] IPHA, International Passive House Association. Available: http://www.passivehouse-international.org/index.php?page_id=65 [Last accessed April 2, 2014].
- [12] Suri, M., Huld, T., Dunlop, E. & Cebecauer, T. 2006 . Photovoltaic Solar Energy Potential in European Countries, European Commission Joint Research Centre.
- [13] YOHANIS, Y.G. and NORTON, B., 2000. A comparison of the analysis of the useful net solar gain for space heating, zone-by-zone and for a whole-building. *Renewable Energy*, **19**(3), pp. 435-442.
- [14] ESTIF, 2012, “Solar Thermal Markets in Europe – Trends and Market Statistics” available from http://www.estif.org/fileadmin/estif/content/market_data/downloads/Solar%20Thermal%20Markets%20in%20Europe%20-%20Trends%20and%20Market%20Stat.pdf
- [15] MCGREGOR, K., 2006. A Comparison of EU Capital Cities for Suitability for Solar Space Heating, *EuroSun 2006*.
- [16] Dincer, I. & Rosen, M.A. 2002, *Thermal Energy Storage, Systems and Applications*, John Wiley & Sons Ltd.
- [17] COLCLOUGH, S.M., 2011. *Thermal energy storage applied to the Passivhaus standard in the Irish climate*, PhD Thesis, University of Ulster.
- [18] Schmidt, T., Mangold, D. 2006, "New Steps in Seasonal Thermal Energy Storage in Germany", *Proceedings of EcoStock: the 10th International Conference on Thermal Energy Storage*.
- [19] Roth, K., Broderick J. 2009, "Emerging Technologies - Seasonal Energy Storage", *ASHRAE Journal*, no. January, pp. 41-42, 43.
- [20], New Houses Completed by Type, Department of the Environment, heritage and local government, 2014 available from : <http://www.environ.ie/en/Publications/StatisticsandRegularPublications/HousingStatistics/>. Last accessed April 2, 2014

- [21] CLARKE, J., COLCLOUGH, S., GRIFFITHS, P. and MCLESKEY, J.T., 2013. A Passive House with Seasonal Solar Energy Store: In Situ Data and Numerical Modeling. *International Journal of Ambient Energy*, , pp. 1-35.
- [22] COLCLOUGH, S.M., 2012. One Passivhaus‘ Search for Zero Carbon, *International Passive House Conference 2012*, pp. 577 - 582.
- [23] Sartori, I. & Hestnes, A.G. (2007) Energy Use in the Life Cycle of Conventional and Low-Energy Buildings: A Review Article. *Energy & Buildings*, 39 pp.249-257.
- [24] Ramesh, T., Prakash, R. & Shukla, K.K. (2010) Life Cycle Energy Analysis of Buildings: An Overview. *Energy & Buildings*, 42 (10), pp.1592-1600.
- [25] United Nations Solar Thermal Energy Technology Fact Sheet. Available: http://www.unep.org/training/programmes/Instructor%20Version/Part_2/Activities/Innovations_and_Technology/Energy/Strategies/Solar_Thermal.pdf Last accessed April 4, 2014.
- [26] KINGSPAN THERMOMAX, , Kingspan Renewables extends warranty to 20 years. Available: <http://www.kingspansolar.ie/news/kingspan-renewables-extends-warranty-to-20-years.shtml> [April/3, 2014].
- [27] SIMONS, A. and FIRTH, S.K., 2011. Life-cycle assessment of a 100% solar fraction thermal supply to a European apartment building using water-based sensible heat storage. *Energy and Buildings*, **43**(6), pp. 1231-1240.
- [28] ELECTRIC IRELAND, 2012, Fuel Mix Disclosure. Available: <https://www.electricireland.ie/ei/residential/manage-your-account/fuel-mix.jsp>.